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# PROPERTIES OF PRINCIPLE TL DOSIMETERS

BY V. K. MATHUR

RESEARCH AND TECHNOLOGY DEPARTMENT

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Of the various techniques that can be used for personnel dosimetry, thermoluminescence dosimetry has emerged as a superior technique due to its manifold advantages over other methods of dose estimation. This has led to the formulation of desired characteristics of a TL dosemeter. Various phosphors have been therefore investigated regarding their suitability for dosimetry. A brief description of important TL materials and their properties is documented in this report.

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## FOREWORD

Of the various techniques that can be used for personnel dosimetry, thermoluminescence dosimetry has emerged as a superior technique due to its manifold advantages over other methods of dose estimation. This has lead to the formulation of desired characteristics of a TL dosemeter. Various phosphors have been therefore, investigated regarding their suitability for dosimetry. A brief description of important TL materials and their properties is documented in this report.

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# CHAPTER 1

## INTRODUCTION

The use of nuclear energy for ship propulsion and the development of nuclear weapons has generated a demand for personal dosimetry of the individual worker on a routine basis. The worker may be exposed to the hazard of $\gamma$-rays, $\beta$-rays and neutrons. Of these three, $\gamma$-rays are very penetrative and plentiful. However, the determination of the radiation exposure for $\gamma$-rays is a straight forward and accurate procedure. The determination of the dose due to $\beta$-rays is difficult because of their low penetration and energy dependence. It is very hard to determine the doses of fast neutrons accurately due to their non-ionizing nature.

Of the various techniques that can be used to estimate the doses of hazardous radiation, thermoluminescence dosimetry (TLD) emerged as the preferred means because of convenience of batch evaluation, reusability, large detection range, linearity and cost effectiveness. More than 3000 minerals exhibit thermoluminescence but only a handful of them have the desired characteristics for a dosemeter, of which only half a dozen are established as good dosemeters. The most commonly used TL phosphors for dosimetry are: (1) Lithium Fluoride (LiF), (2) Lithium Borate ($Li_2B_4O_7$), (3) Calcium Fluoride ($CaF_2$), (4) Calcium Sulphate ($CaSO_4$), (5) Aluminum Oxide ($Al_2O_3$), (6) Beryllium Oxide (BeO), and (7) Magnesium Borate ($MgB_4O_7$).

# CHAPTER 2

## DOSE LINEARITY

To be a good dosemeter, a TL material must have a linear dose-TL signal relationship. For this circumstance, the thermoluminescence signal $Q_{TL}$ and absorbed dose D are related as follows

$$Q_{TL} = \alpha \ Y_{TL} \ D \qquad\qquad (1)$$

where $\alpha$ is a constant of proportionality and $Y_{TL}$ is energy emitted as light per unit mass of the phosphor per unit absorbed dose. In the linear region $Y_{TL}$ is constant.

Table 1 gives the dose ranges within which detectors show a linear behavior. In general, the deviation from linearity is due to the presence of supra-linearity. The origin of this phenomenon is not completely understood.

### TABLE 1. LINEARITY RANGES

| TL Material | Linearity range for $^{60}CO$ gamma rays (order of magnitude) (rad) |
|---|---|
| LiF:Mg,Ti | $10^{-2} - 10^{2}$ |
| $Li_2B_4O_7$:Mn | $10^{-2} - 10^{2}$ |
| $CaF_2$:Mn | $10^{-4} - 10^{3}$ |
| $CaF_2$:Dy | $10^{-5} - 10^{3}$ |
| BeO | $10^{-2} - 10^{2}$ |
| $CaSO_4$:Dy | $10^{-4} - 10^{3}$ |
| $CaSO_4$:Tm | $10^{-4} - 10^{2}$ |
| $Al_2O_3$ | No linear characteristics |

It may be remarked that in the supralinearity region, the TL detector maintains the new sensitivity even after the dose readout. To restore its initial sensitivity a complete annealing cycle is needed. Beyond the supralinearity range "saturation" sets in due to the decrease in the number of available traps. This determines the upper dose limit for each detector, which is usually estimated to be 20% below the saturation value.

Lower dose limit or detection threshold is defined as the smallest dose that can be distinguished significantly from a zero dose and is taken as three times the standard deviation of the zero dose reading expressed in units of absorbed dose.

## CHAPTER 3

## FADING

The dose stored in a phosphor may slowly be removed because of the thermal release of electrons or holes from their traps. This is called "Fading." A good TL dosemeter should not exhibit significant fading over the time the dosemeter is stored before dose read out.

The release of electrons and holes from their traps and consequently their recombination is a statistical phenomenon. The probability of detrapping is a function of temperature, which is given by

$$P = S \exp (- E/_{kT})$$

Where S = vibrational factor characteristic of the trap, E = activation energy, k = Boltzmann's constant, and T = absolute temperature. The half-life of the phenomenon is given by

$$\tau = 0.693 \ P^{-1} \tag{2}$$

Table 2 gives the temperature of the different peaks and information on the stability of the carriers in the corresponding traps at 20°C for some phosphors.

### TABLE 2. GLOW PEAK TEMPERATURES AND HALF-LIFE/FADING

| TL Material | Peak Number | Emission Temp (°C) | Half-life/Fading |
|---|---|---|---|
| LiF:Mg | I | 70 | 5 min |
| | II | 130 | 10 hr |
| | III | 170 | 0.5 yr |
| | IV | 200 | 7 yr |
| | V | 225 | 80 yr |
| CaF$_2$:Mn | I | 260 | 1% per day |
| CaF$_2$:Dy | I | 120 | |
| | II | 140 | |

TABLE 2 (cont.)

| TL Material | Peak Number | Emission Temp ($^\circ_C$) | Half-life Fading |
|---|---|---|---|
| | III | 200 | 25% per month |
| | IV | 240 | |
| BeO | I | 70 | |
| | II | 160 | |
| | III | 180 | 0% per 5 months |
| | IV | 220 | |
| $Li_2B_4O_7$:Mn | I | 50 | |
| | II | 90 | |
| | III | 200 | 10% per 2 months |
| | IV | 220 | |
| $CaSO_4$:Dy | I | 80 | |
| | II | 120 | |
| | III | 220 | 7% per 6 months |
| | IV | 260 | |
| $Al_2O_3$ | I | 103 | 1 hr |
| | II | 123 | 140 hrs |
| | III | 164 | 115 d |
| | IV | 236 | $1.8 \times 10^7$ yr |

It is easy to conclude from the table above that shallow traps have smaller half lives and will fade more rapidly than deep ones due to a larger transition probability. Fading can lead to large errors in dose assessment. In some instances, the shallow traps which are responsible for fading are emptied intentionally by post-irradiation anneal in a separate oven or in the reader as a part of the readout process. In addition to thermal fading, any exposure to artifical light or sunlight can modify the actual dose due to the following phenomena:

a.   spurious dose due to the creation of electron-hole pairs by absorption of near U-V light.

b.   the loss of latent dose information due to optical fading arising through optical stimulation of trapped electrons.

However, the effect of light exposure on detectors can be easily avoided by keeping them in a light tight environment.

# CHAPTER 4

## ANNEALING

Each TL material used in dosimetry requires pre-dose annealing for restoring its initial conditions after an irradiation. Annealing results in emptying the traps of the phosphor completely after the irradiation and readout cycle and it also stabilizes the electron traps in order to obtain, within narrow limits, the same glow curves even after repeated irradiations and thermal treatments. Annealing is very critical in the case of LiF, because if the procedure is not always identical, one can obtain significantly different glow curves from repeated irradiations to the same exposure.

In Table 3 are summarized the annealing procedures for several TL materials used in practice.

### TABLE 3. ANNEALING PROCEDURES

| TL MATERIAL | Annealing Procedures | Pre-read Annealing |
|---|---|---|
| LiF(TLD 100) | 1 h at 400°C+24 h at 80°C (or 2 h at 100°C) | 10 min at 100°C |
| $Li_2B_4O_7$:Mn | 15 min at 300°C | 10 min at 100°C |
| BeO | 15 min at 600°C | |
| $CaF_2$:Dy (TLD) 200) | 1 h at 400°C | |
| $CaF_2$:Mn | 1 h AT 400°C | |
| LiF (PTL 700) | 240-250°C in the reader | Performed in the reader |

A TL material which is a candidate for dosimetric applications should not go through any physicochemical changes during the repeated annealing and exposures. This ensures that the glow curve, TL yield and non-radiation induced light emission must not change during storage, irradiation and dose readout. Stability of a phosphor is measured as reproducibility by calculating the standard deviation of a repeated set of measurements under the same exposure and reading conditions.

# CHAPTER 5

## DOSE RATE DEPENDENCE

LiF, $Li_2B_4O_7$:Mn and BeO were studied for their dose rate dependence by exposing these detectors to very short pulses ($\approx 10^{-7}$ s) of high intensity x-rays. It was observed that:

1. the response of LiF is not modified up to an exposure of $1.5 \times 10^{11}$ $Rs^{-1}$;

2. the response of BeO is not modified up to $5 \times 10^{11}$ $Rs^{-1}$;

3. the response of $Li_2B_4O_7$ is independent of dose rate up to $10^{12}Rs^{-1}$.

The independence of TL response to dose rate points out the possibility of their use near installation delivering photons in very short pulses.

# CHAPTER 6

## SPURIOUS THERMOLUMINESCENCE

A spurious signal is sometimes obtained due to tribo-thermoluminescence (TTL), which increases the detection threshold and the error in the dose assessment. This phenomenon is eliminated when the detector is heated in an inert atmosphere of argon or nitrogen. It is negligible in the dose measurement at therapy levels (doses of the order of several hundred rads) but can be significant for personnel dosimetry. $CaF_2:Mn$ exhibits a TTL peak around 360°C in air. Argon ambient shifts this peak to 460°C, although it does not suppress it. The TTL signal in air is no more than one fifth the $\gamma$-ray response in $CaF_2:Mn$.

## CHAPTER 7

## CHARACTERISTICS OF TL DOSEMETERS

We describe below in brief details the individual characteristics of various TL phosphors used in dosemeters.

LITHIUM FLUORIDE

LiF is the most important TL material used for dosimetry. Due to its approximately tissue equivalent response, LiF has found wide application in personnel dosimetry and health physics. However, in practice it has a comparatively poor TL yield and complex glow peak structure. Thermoluminescence of LiF is attributed to the presence of Mg and Ti impurities. The commerical products marketed by Harshaw are termed as TLD 100, TLD 600 and TLD 700 according to their preparation from natural lithium or lithium enriched with $^6$Li or $^7$Li. A similar quality LiF, stabilized with Sodium was studied in France and marketed by Desmarquest under the name PTL 710, 716 and 717. These products, unlike Harshaw products, do not require systematic regeneration before each usage.

The glow curve of LiF consists essentially of six peaks as shown in Figure 1. These peaks are numbered consecutively in ascending order of their peak temperature. The peak V, which occurs at 225°C is normally used for dosimetric purposes. Low temperature peaks I, II and III are relatively unstable and must be suppressed by a thermal regeneration process. For sodium stabilized LiF, annealing is necessary only for heavily irradiated samples. Table 4 shows the peak temperature and the half-life of corresponding trap levels.

TABLE 4. PEAK TEMPERATURE AND HALF-LIFE OF
CORRESPONDING TRAP LEVEL

| Phosphor | Peak No. | Peak Temperature (°C) | Half-Life |
|---|---|---|---|
| LiF TLD | I | 65 | 5 min |
| | II | 120 | 10 h |
| | III | 160 | 0.5 yr |
| | IV | 195 | 7 yr |
| | V | 210 | 80 yr |
| | VI | 275 | not measured |
| LiF PTL | I | 80 | 20 min |
| | II | 130 | 80 hr |
| | V | 220 | $1.3 \times 10^7$ yr |
| | VI | 280 | not measured |

For both LiF TLD and LiF PTL the maximum of the emission occurs at 400 nm.
The emission is identical for all traps. The intrinsic TL efficiency (the ratio
of energy emitted in the form of light per unit of phosphor mass and absorbed
dose) is 0.04, which is low compared to other dosemeters. The effective atomic
number of LiF number of LiF is close to that of tissue ($Z_{eff}$ (LiF) = 8.14,
$Z_{eff}$(tissue) = 7.4). Therefore, its response varies only slightly with photon
energy: it varies by about 30% between 3.0 keV and 1.2 MeV.

LITHIUM BORATE

Lithium Borate has been activated by Mn as well as Cu to synthesize TL
dosemeters. A mixture of 32.5g of lithium carbonate and 108.96g of boric acid
is added to a 5 ml aqueous solution of 75 mg of $MnCl_2 4H_2O$ and subsequently
heated at 100°C for 12 h. The product is placed in a platinum crucible, heated
up to 950°C and then rapidly cuoled. The crystalline mass is then ground and
graded between 75 and 175 µm. The glow curve of $Li_2B_4O_7$:Mn is shown in
Figure 2. It can be divided in two distinct parts:

(1) one part consists of unstable peaks between 50°C and 90°C
(2) the second part consists of a double peak, the first of which appears at 200°C at low doses and the second of which app _rs at 220°C for doses in excess of 50 rad. With high LET radiation another peak occurs at 350°C.

The double peak, used for dosimetry, fades 10 and 37% in 2 and 13 months at ambient temperature. The addition of $SiO_2$ (0.5%) to the phosphor reduces the influence of humidity on lithium borate which is very hygroscopic. This phosphor can be used without regeneration. For zeroing the phosphor after high doses it is sufficient to reheat the material at 300°C for 35 min.

The maximum wavelength of emission from $Li_2B_4O_7$:Mn is about 600 nm. This limits the sensitivity of this phosphor to 1/2 of that of LiF with an S20 photocathode in spite of the fact that the intrinsic sensitivity of $Li_2B_4O_7$:Mn is a factor of 1.83 higher than that of LiF. Doping $Li_2B_4O_7$ with Cu results in two TL peaks at about 120°C and a dominant, stable peak at 205°C. The sensitivity of this phosphor is 20 times higher than $Li_2B_4O_7$:Mn. One of the factors contributing to this relatively high sensitivity is the favorable spectral location of the TL emission which peaks at 368 nm.

CALCIUM FLUORIDE

$CaF_2$ is considerably more sensitive than Lithium Fluoride; the minimum detectable limit is about 10 times less and it has a larger linear dose response range but it is not tissue equivalent ($Z_{eff}$ = 16.57). Natural $CaF_2$ has a favorable emission at 375 nm, although it exhibits different dosimetric characteristics depending upon the origin of the sample.

Mn doped (3%) $CaF_2$ is synthesized by co-precipitation of $CaF_2$ and $MnF_2$ from a solution of $CaCl_2$ and $MnCl_2$ in ammonium fluoride. The precipitate is dried and heated in an oven at 1200°C under neutral ambient. The product is then crushed and graded and finally pressed or sintered. The TL glow curve consists of a main peak at 260°C as shown in Figure 3. This peak is a convolution of several overlapping peaks which results from several trap levels located very close to each other. Due to the presence of high temperature peaks, which cause evaluation difficulties when the phosphor is exposed to high doses, the sample must be reheated after a high dose to empty the deeper trap levels before being used for low-dose measurements. $CaF_2$ fades at t he rate of 1% per day. The light emission at 500 nm is characteristic of Mn. The intrinsic sensitivity of $CaF_2$:Mn is 0.44.

$CaF_2$:Mn is the mainstay of Navy's dosimetric program. It has great merit in stability, clean dosimetric peak and simplicity of operation. However, this phosphor exhibits an anomalous fading. This fading is much more rapid initially than expected from its high temperature glow peak. Schulman attributed this phenomen to the shifting of the glow peak at high heating rates to the temperature where thermal quenching takes place. Anomalous fading has been observed in a number of phosphors since then and is now generally attributed to the tunnelings of electrons from the traps to the nearest luminescent center non-radiatively.

Recently, single crystals of $CaF_2$:Mn obtained from Optovac and Navy dosemeters supplied by Harshaw Chemicals were studied at the Center. It was interesting to observe that the glow curve spectrum in these two products was not identical. Optovac samples exhibited an additional glow peak in 50-80°C range.

Dysprosium doped $CaF_2$ is more sensitive than $CaF_2$:Mn. The glow curve of $CaF_2$:Dy consists of six peaks which are difficult to separate (see Figure 4). This is true for the unstable peaks at 120°C and 140°C as well as for the stable peaks at 200°C and 250°C. Two higher temperature peaks appear at 340°C and 400°C. It is not a stable material and exhibits strong fading. A thermal treatment of 10 min at 80°C reduces the fading from 25 to 13% per month.

The TL emission of $CaF_2$:Dy exhibits three maxima which occur at 460, 483 and 576 nm. The presence of the numerous peaks in the glow curve results in a complicated dose response curve. Therefore, measurements based on light integration only make sense. It is used mostly for the measurement of low doses but is being replaced by calcium sulphate activated with dysprosium, which is more stable.

## CALCIUM SULPHATE

$CaSO_4$ is one of the most sensitive TLD products used in dosimetry. $CaSO_4$:Mn has been used for detection of doses as low as 20 μrad but exhibits very strong fading as its TL peak occurs at 90°C. $CaSO_4$:Dy and $CaSO_4$:Tm are the most interesting phosphors in $CaSO_4$ series, since their response is considerably more stable.

To synthesize these phosphors, 75 mg of powdered dysprosium oxide ($Dy_2O_3$) or 80 mg thulium oxide ($Tm_2O_3$) are dissolved in 250 c.c. of concentrated sulphuric acid. The solution is heated in a crucible up to 250°C and 34.4 g of calcium sulphate ($CaSO_4$:$2H_2O$) is added. The solution is then evaporated at 300°C until $CaSO_4$ crystalizes. The crystals are pulverized and graded to 75-200 μm. This powder is heated at 750°C for 2 h in an aluminum oxide crucible in air and subsequently heat treated at 400°C for 15 min.

The glow curve of $CaSO_4$:Dy/Tm exhibit two low temperature peaks at 80°C and 120°C. The dosimetric peak occurs at 220°C (see Figure 5). A high temperature peak occurs at 250°C for doses in excess of several thousand rads for $CaSO_4$:Dy. Low temperature peaks are eliminated by post-dose annealing at 100°C. Both these phosphors are light sensitive. The luminescence spectrum of $CaSO_4$:Dy has two emission peaks, one at 478 nm and another at 571 nm. $CaSO_4$:Tm emits a main peak at 452 nm and less important peaks at 360, 470 and 520 nm.

$CaSO_4$:Dy and $CaSO_4$:Tm are both more sensitive to photon radiation than LiF. The minimum detection limit is as low as 0.1 mrad. The tribothermoluminescence noise is negligible. The effective atomic number of $CaSO_4$:Dy/Tm is 15.6. The response to 30 keV photon radiation is 11 times greater than that obtained with ^{60}Co radiation.

## ALUMINUM OXIDE ($Al_2O_3$)

Aluminum oxide is low cost material since it has other industrial applications. It exhibits four peaks at 103°C, 123°C, 164°C and 236°C. The first three peaks are merged as shown in Figure 6. The dosimetric peak (IV) appears with bakes at temperatures greater than 1000°C when Alumina is completely dehydrated. This peak is attributed to sodium impurity. The trapping state corresponding to peak IV is very stable (half-life at 20°C = $1.8 \times 10^7$yr). The heating cycle during the readout process does not affect the glow curves. It can be regenerated by annealing at 500°C for 1 h. $Al_2O_3$ should be stored away from light after irradiation.

$Al_2O_3$ emits strongly in the 650 nm region and weakly between 390 and 550 nm. It is the latter emission which is detected with an ordinary commercial TL reader.

Using peak IV only, a minimum dose of 100 mrad can be detected with $N_2$ flushing. Without $N_2$ flushing triboluminescence results in an increase of the lower detection threshold to about 10 rad. $Al_2O_3$ is less photon energy dependent than $CaSO_4$.

## BERYLLIUM OXIDE

This phosphor is commercially available in microcrystalline powder form. It is extremely toxic when dispersed in air as a fine powder. Sintered pellets are also available which present no danger as long as abrasion of the surface and therefore production of powder and dust is avoided. The inclusion of sodium increases the sensitivity of the pellets. A typical product exhibits two stable neighboring peaks at 180°C and 220°C respectively. The second peak appears at the relatively high doses and becomes preponderant about 1000 rad. Its TL emission extends into the ultraviolet.

By using a photomultiplier with quartz window, the sensitivity of BeO equals that of LiF. Dosemeters sensitised with sodium are very sensitive and allow the measurement of doses down to 1 mrad. This material is highly light sensitive and exposure to fluorescent light accelerates fading by optical stimulation. It is a good tissue equivalent (Z = 7.13) material. It is 60% more sensitive to 10-50 keV photon radiation compared with [60]Co γ-rays. Unlike LiF and $Li_2B_4O_7$:Mn, BeO exhibits an increased response with increasing LET. This property of BeO may be utilized for identifying the type of incident radiation.

## MAGNESIUM BORATE

Magnesium Borate dosemeters doped with Dysposium or Thulium have been recently reported. A little amount of yttrium is used as a sensitiser of the TL emission. The material is used in the form of sintered dosemeters. $MgB_4O_7$:Dy emits a green yellow band, while $MgB_4O_7$:Tm emits a blue band. The emission of the Dy activated dosemeter is unaffected by the presence of a co-activator, however a co-activator changes the emission in Tm activated material into a green yellow light. These TL dosemeters are seven times more sensitive than LiF

TLD 100, while its effective atomic number is similar to that of LiF. This dosemeter is not light sensitive or hygroscopic and can detect exposure of 1 mrad. It does not require annealing before irradiation or after read-out. It fades less than 10% during first 60 d after irradiation when an appropriate post irradiation annealing is applied.

# CHAPTER 8

## PHOTON RESPONSE

For any practical dosimetric application, the knowledge of energy response is important. The energy response is a measure of the energy absorbed in the TL material used in comparison to the energy absorbed in a material taken as the reference, when irradiatd at the same exposure. Normal reference materials are air and tissue. The energy response can easily be calculated as the ratio between the mass energy absorption coefficients of the detector and air respectively in the energy range up to 3 MeV.

If $S(E)$ is the energy response one has

$$S(E) = (\mu_{en}/\rho)_d / (\mu_{en}/\rho)_{air}$$

where d stands for detector.

Since $(\mu_{en}/\rho)_d$ commonly refers to a compound or a mixture of different elements, the additivity rule must be used to calculate it at every energy value

$$(\mu/_{en}/\rho)_d = (\mu_{en}/\rho)_1 w_1 + (\mu_{en}/\rho)_2 w_2 + \cdots + (\mu_{en}/\rho)_i w_i + \cdots$$

where $(\mu_{en}/\rho)_i$ is the mass energy absorption coefficient of the $i^{th}$ element and $w_i$ is its fraction by weight. For dosimetric purposes, a material with a constant energy response over the energy range of interest is desirable. This can be achieved by choosing materials with a low effective atomic number Z.

# CHAPTER 9

## β-RAY RESPONSE

TL materials are sensitive to β-rays. However, due to the large dimensions of the grains of a phosphor powder and/or large thickness of a compacted detector, the response of the detector decreases sharply in the low energy range of β-rays. Laser heating of thin film detectors is being studied presently to detect low energy β-rays.

# CHAPTER 10

## NEUTRON RESPONSE

TL dosemeters are now being increasingly used to monitor neutron doses. There is a need to monitor neutron doses in mixed $n,\gamma$ fields. The sensitivity to neutrons of TL phosphors depends on their thickness, isotropic composition, irradiation condition and, to some extent, on the activators. LiF and $Li_2B_4O_7$ can be synthesized with different abundances of $^6Li$ and $^{10}B$, thus increasing markedly their slow neutron sensitivity. Table 5 shows the response of a number of TL materials to a fluence of $10^{10}$ thermal neutrons $cm^{-2}$ in terms of an equivalent exposure to $^{60}Co$ gamma rays.

### TABLE 5. SLOW NEUTRON SENSITIVITY

| Material | Response($10^{10}$ $cm^{-2}$)/Response(R of $^{60}Co$ gamma ray) |
|---|---|
| LiF (TLD 100) | 350 |
| $Li_2B_4O_7$:Mn | 310 |
| LiF (TLD 600) | 1930 |
| LiF (TLD 700) | 1.5 |
| $CaF_2$:Mn | 0.6 |
| $CaSo_4$:Dy | 0.5 |
| BeO | 0.3 |

The response of TL materials to fast neutrons is rather low. Various techniques have been tried to increase the neutron response of the main dosimetry peaks such as (i) using a hydrogenous material to provide recoil protons, (ii) using a foil of fissionable material and detecting the fragments and (iii) using a moderator to thermalise the neutrons. $CaSO_4$:Dy in conjunction with proton radiator has proven to be a good tool for the detection of fast neutrons by using laser heating technique.
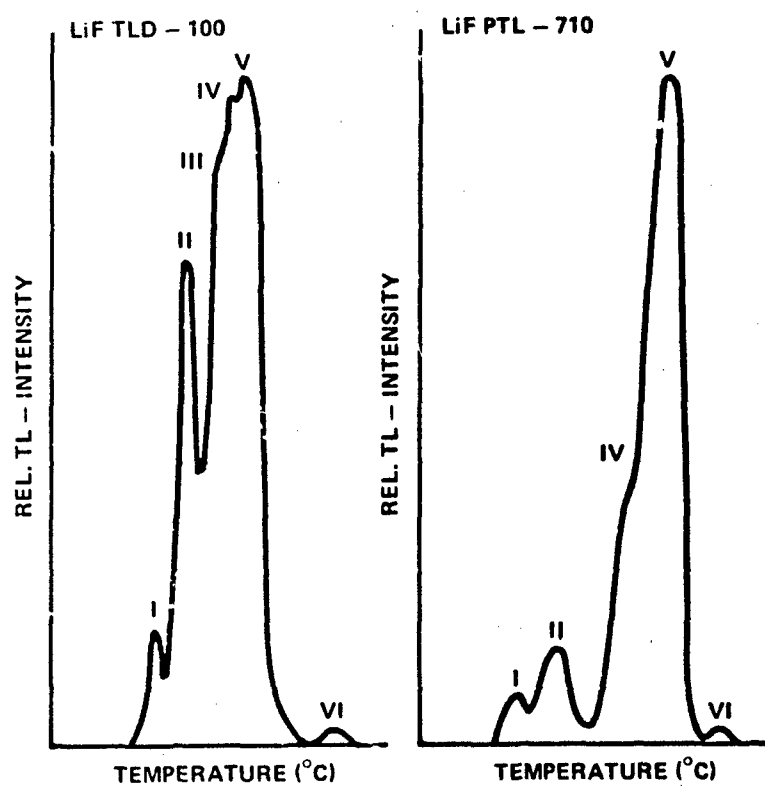
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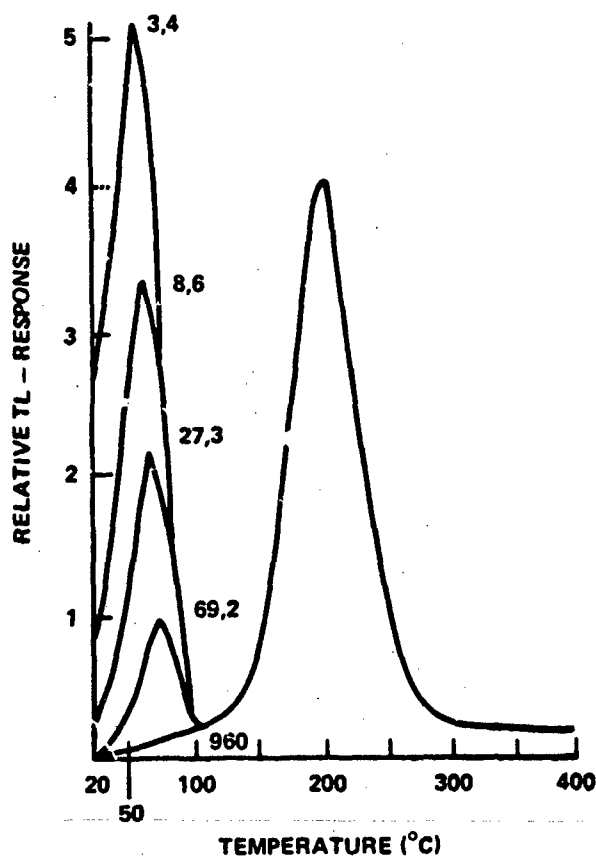FIGURE 1. GLOW CURVES OF LiF TLD 100 (HARSHAW) AND LiF PTL 710 (DESMARQUEST)

FIGURE 2.  GLOW CURVES OF $Li_2B_4O_7$:Mn AT 3.4, 8.6,
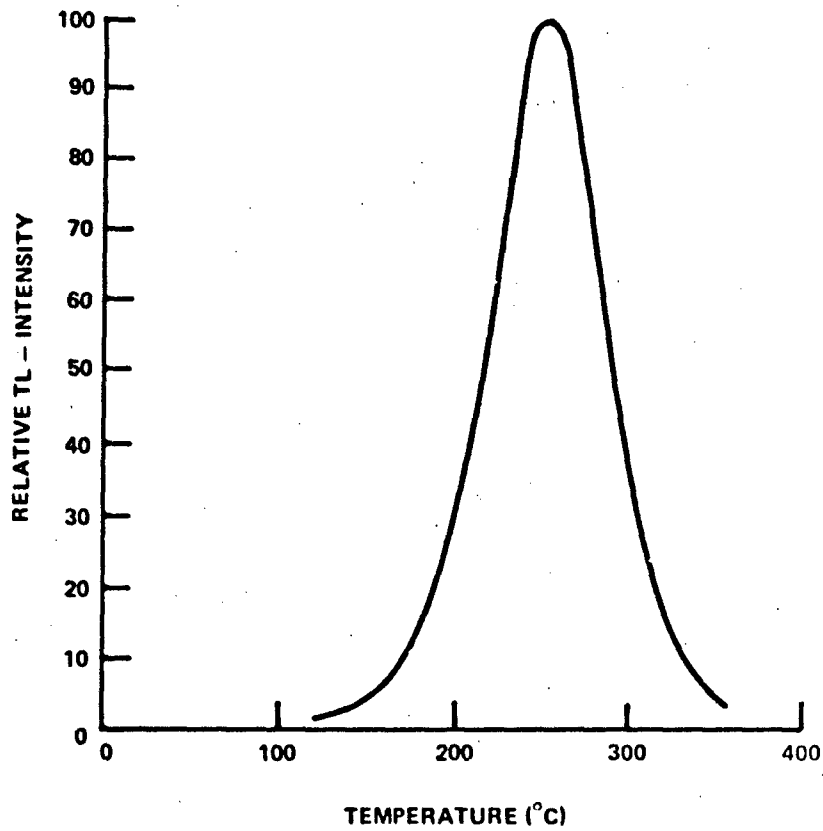27.3, 69.2 AND 960 MIN,
RESPECTIVELY AFTER IRRADIATION

FIGURE 3.   GLOW CURVE OF CaF$_2$:Mn
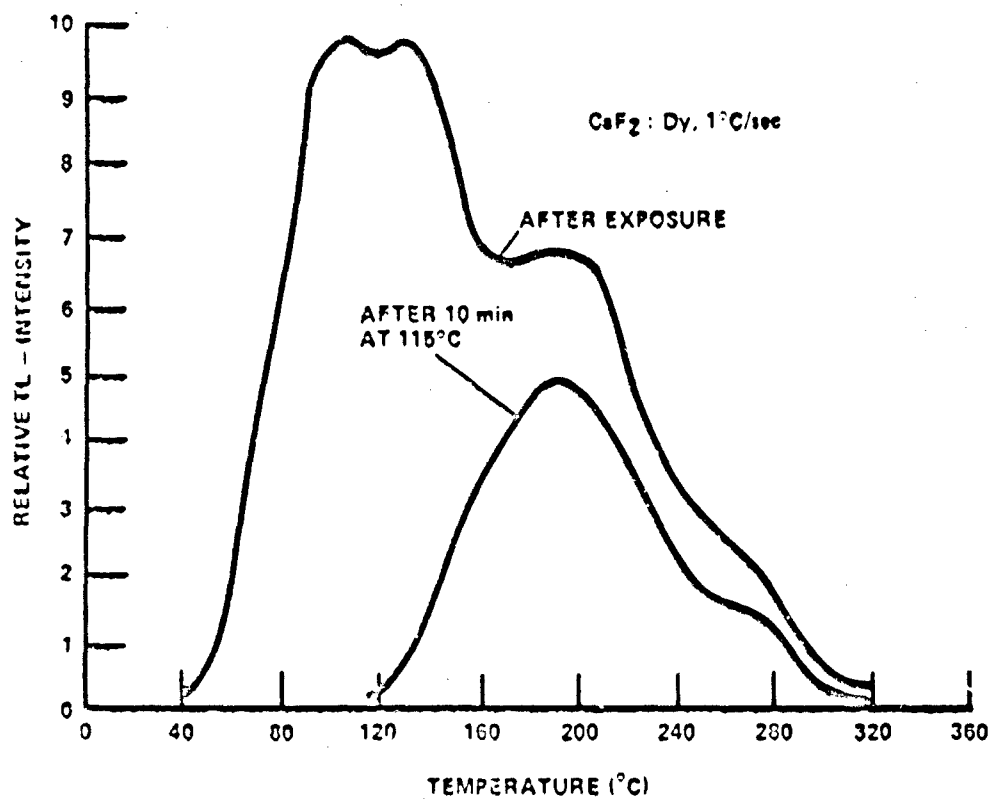
FIGURE 4.  GLOW CURVE OF CaF$_2$:Dy
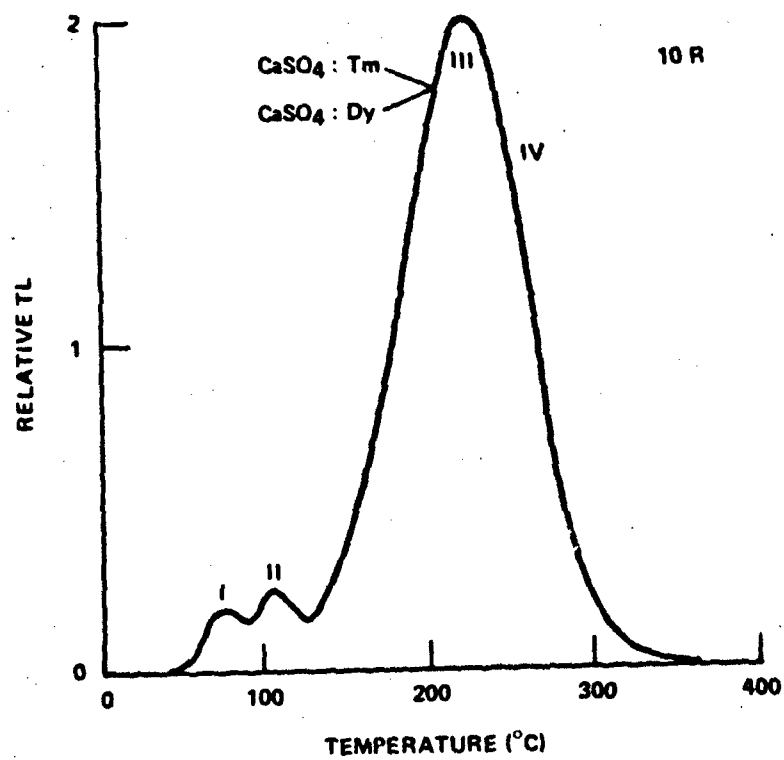
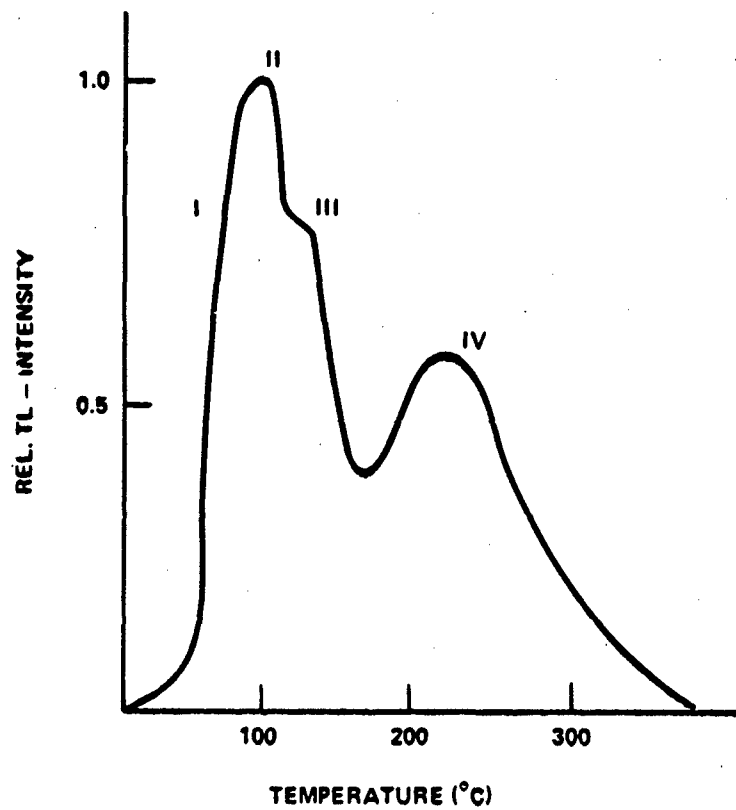FIGURE 5.   GLOW CURVE OF $CaSO_4$:Dy AND $CaSO_4$:Tm

FIGURE 6. GLOW CURVE OF $Al_2O_3$

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